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Cost Estimating Procedure for Unmanned Satellites

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Historical costs from 11 unmanned satellite programs were analyzed. From these data, total satellite cost estimating relationships (CERs) were developed for use during preliminary design studies. A time-related factor, which it is believed accounts for differences in technology, was observed in the data. Stratification of the data by type of payload was also found to be necessary. Cost differences that stem from production quantity variations were accounted for by adjustment factors developed from standard learning curve theory. An example to illustrate use of the CERs is provided.

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CONTENTS

TABLES

FIGURES

I. INTRODUCTION

In recent years, emphasis has been placed on obtaining greater visibility and on improving the accuracy of satellite cost estimates by dealing with components and major assemblies rather than the total satellite. The problem remained, however, of estimating satellite costs when little design detail was known, particularly during the preliminary phases of satellite programs. To remedy this situation, historical data collected over the years within the Resource Analysis Directorate were restudied with a view toward developing total satellite cost estimating relationships (CERs).* In the process, it was found that an adjustment factor was needed to account for what appear to be time-related improvements in technology. In addition, stratification according to payload type was necessary. The results of this study, together with an example that illustrates how to use the CERs, are presented in the following sections.

*This reanalysis was also prompted by another study that had as its objective the estimation of cost when only satellite dry weight, mission (payload) type, date of first flight, and total quantity flown were known.

II. PROCEDURE

In estimating Aerospace equipment cost, the principal method employed has been to use data from past and recently completed programs as a basis for extrapolating into the future. Over the last ten years, cost and related technical data were gathered and analyzed on twenty-two unmanned satellite programs. In the present study, sufficient data were extracted from eleven programs within the existing data base to support cost extrapolations when only meager satellite characteristics are known. The following paragraphs describe the steps taken in the analysis.

A. PROBLEM DEFINITION

The purpose of this study is to develop a cost estimating procedure for a complete satellite, i.e., the spacecraft (composed of housekeeping subsystems) plus the mission equipment or payload. The first step is the selection of a data base containing the necessary information. Data for the satellites listed in Table 1 contain the following characteristics required to develop the CERs and to permit their practical application: (1) costs segregated into recurring and nonrecurring categories, (2) costs of subsystems plus mission equipment, (3) number of satellites produced and flown, (4) weight information (dry and expendable), (5) dates of launches, (6) time periods during which expenditures were incurred, and (7) different types of satellite missions.

Segregation of costs into recurring and nonrecurring categories permits the identification of R&D and unit cost, which are the primary ingredients of CERs. To find total satellite cost, mission equipment and spacecraft cost must be obtained and aggregated. The number of satellites produced must be known so that average unit cost can be calculated and normalized for a constant number of satellites -- for this study a quantity of five was used. Weight information is needed because it is the principal independent variable in CERs. (Weights of expendables or kick motors can unduly bias cost

Table 1. Satellite Programs in Data Base

TACSAT	AE-C	DMSP
DSP	ATS-F	OSO-I
TIROS-M	SMS	GPS
DSCS-II	P72-2	

estimates downward; accordingly, such weights are omitted from the total to obtain satellite dry weight.) Launch date information, in particular first flight data, can be used as a surrogate for time in measuring the effects on cost of technology change over the years. The time period during which expenditures were incurred was used to normalize cost (through price indexes) to a constant base year. The sample of satellites should be extensive enough to treat future needs and to allow stratification by type, if required. (Accordingly, the programs listed in Table 1 consist of communications, navigation, meteorological, scientific experiment, and mosaic radiometer satellites.)

B. TIME-RELATED TECHNOLOGY FACTOR

It has been observed that, despite inflationary pressures of the past decade, the costs of certain satellite components have decreased, e.g., photovoltaic solar cells and integrated circuits have experienced up to tenfold cost decreases. Increased use of previously developed components such as standardized thrusters, transmitters, and horizon sensors has also served to reduce satellite subsystem costs in both nonrecurring and recurring categories. Because each satellite design is a mixture of subsystems and mission equipment of varying complexity, it is difficult to quantify precisely such technology improvements over time. If the costs of satellites in the data base are normalized to a constant weight and plotted versus time, a downward trend should be observable. The results of such an analysis are shown plotted against the year of first flight in Figures 1 and 2. Although there is

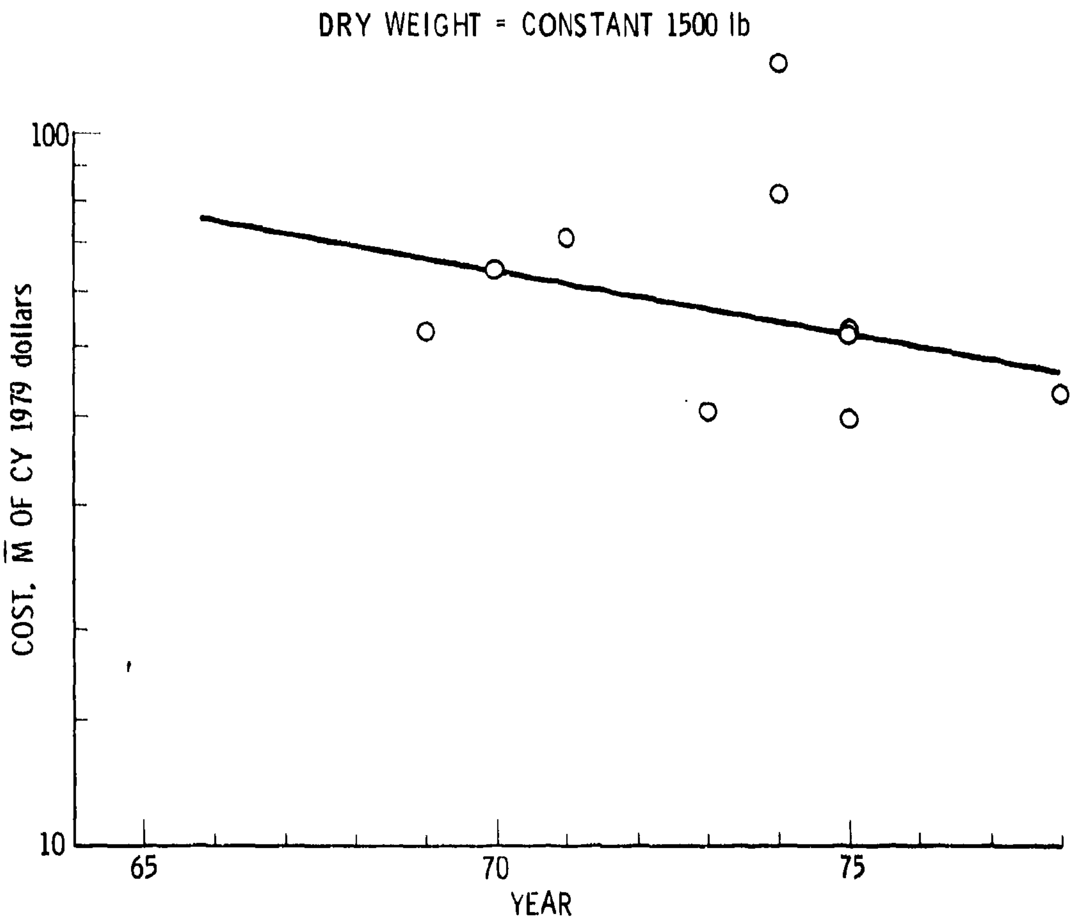

Figure 1. Normalized Nonrecurring Satellite Costs

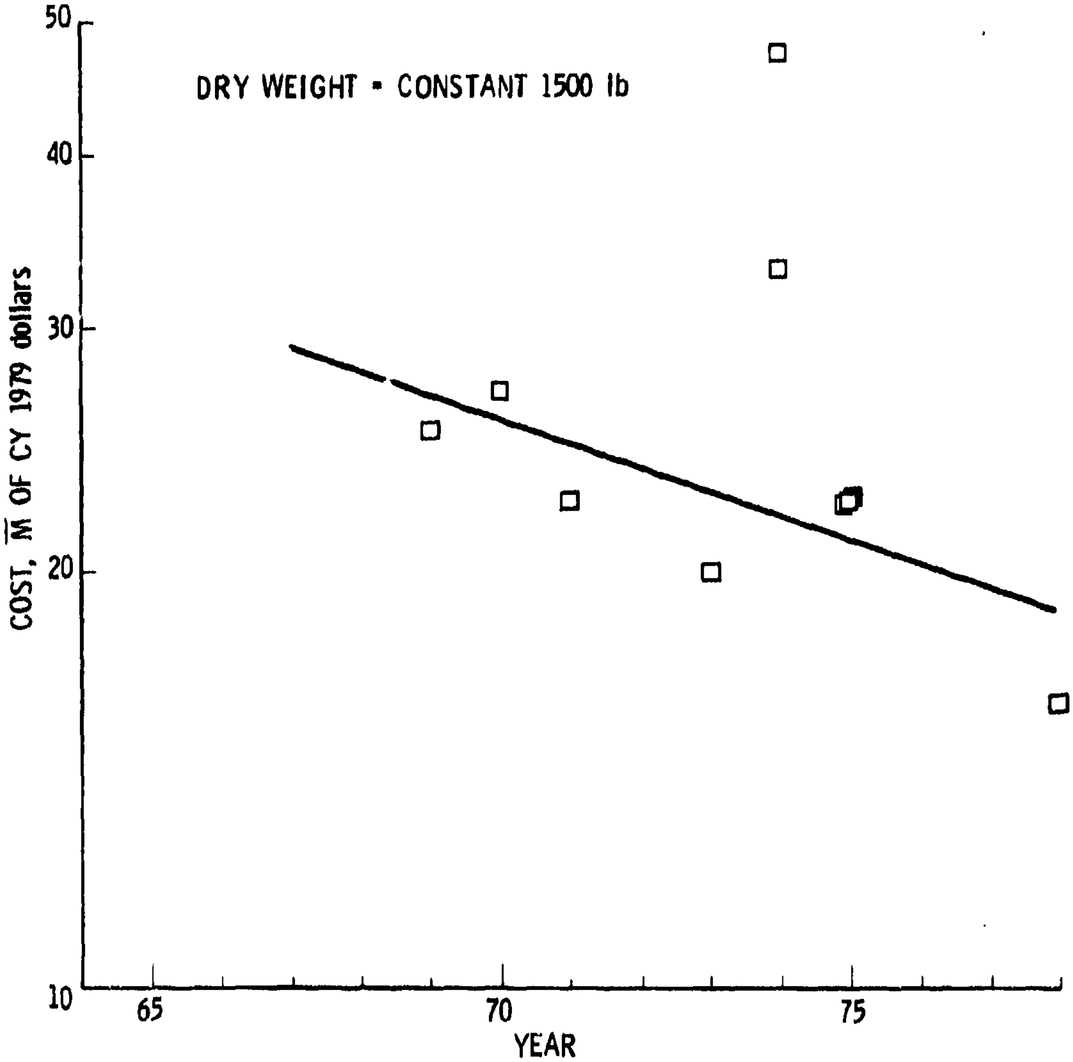

Figure 2. Normalized Recurring Satellite Costs

extensive scatter, these data appear to justify a downward trend with time.* (Certain points can be given less weight in the plot, e.g., it is known that the highest outlying point covers a satellite with a mix of advanced communications equipment and scientific experiments. It also incurred unusually high on-orbit operations expenditures. The left-most point represents a single satellite that was subjected to program cancellation. Such considerations should moderate their importance in any plot.) The year of first flight is used as a surrogate for technology.** Insufficient information was available concerning the mission equipment on older (early 1960s) programs; accordingly, only programs within the last ten years were considered.

The trends from Figures 1 and 2 may also be considered to be a measure of productivity gain in the satellite industry, i.e., for the same constant dollar of input there is an increasing satellite output as time progresses. This observed relationship represents a decrease in satellite costs of approximately four percent per year and can be reformulated into a technology (or productivity) factor for adjusting the cost of past years' satellite programs to current year (1979) technology as

$$F_{cy} = 0.96^{(CY-Y)} \tag{1}$$

where

F_{cy} = technology factor to adjust cost to curent year of technology

Y = year of first launch

CY = current year of technology (1979)

*If spacecraft (excluding mission equipment) are considered, a larger sample is available for analysis, and the trend is unmistakable.

**It is recognized that because of varying engineering lead times, the technological state of the art at the year of first launch is not an accurate representation of technology. However, because all satellite programs are subjected to such variation, it is judged to be a relatively accurate measure from among those that are available.

When cost estimates of future satellites are to be made, the technology factor for such an application is

$$F_y = 0.96^{(Y-CY)} \tag{2}$$

where

F_y = technology factor to adjust the current year cost (and associated technology) to the future year Y technology.

C. DEVELOPMENT OF CERs

For the satellites listed in Table 1, cost information had been previously segregated into nonrecurring and recurring categories. The recurring category had been normalized to an average unit cost for a quantity of five. For this study, a price index factor was used to adjust the data base cost to constant 1979 dollars. To adjust for the effects of technology over time, Eq. (1) was used with CY set to 1979. The results of these adjustments are shown in Figures 3 and 4 where they are plotted versus satellite dry weight (total launched weight less solid and liquid propellants) for nonrecurring and unit cost categories, respectively.

With the exception of two points in Figure 3 (one a mosaic radiometer), the nonrecurring cost data are clustered about the lower trend line represented by

$$C_d = aF_yW_d^{0.678} \tag{3}$$

where

C_d = cost of satellite development in millions of constant CY 1979 dollars and 1979 technology

a = 1.09 for mosaic radiometer satellite missions

a = 0.315 for other satellites

W_d = dry weight of satellite, lb

F_y = 1.0 for 1979 technology, i.e., Y = CY = 1979

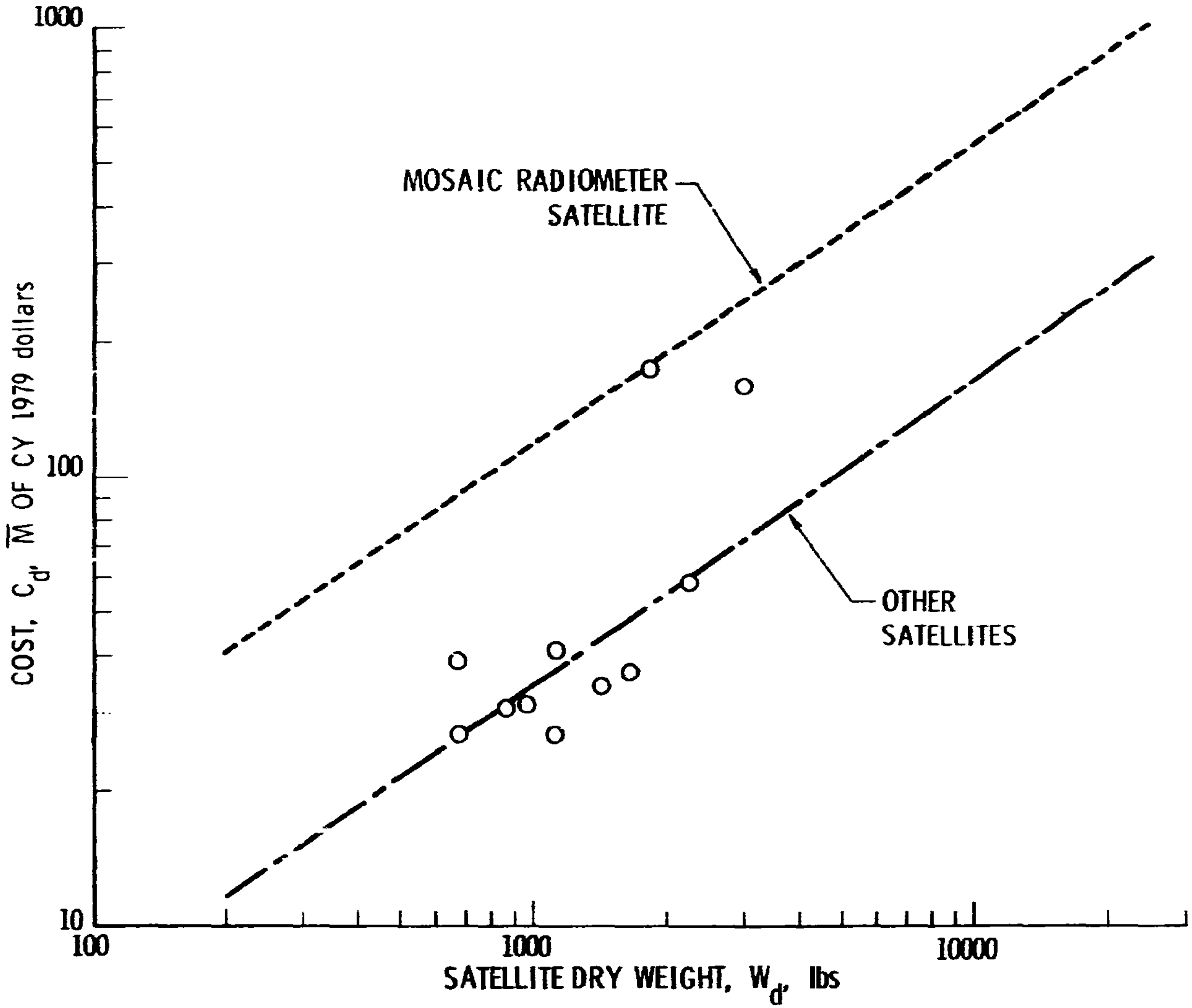

Figure 3. Nonrecurring Satellite Costs

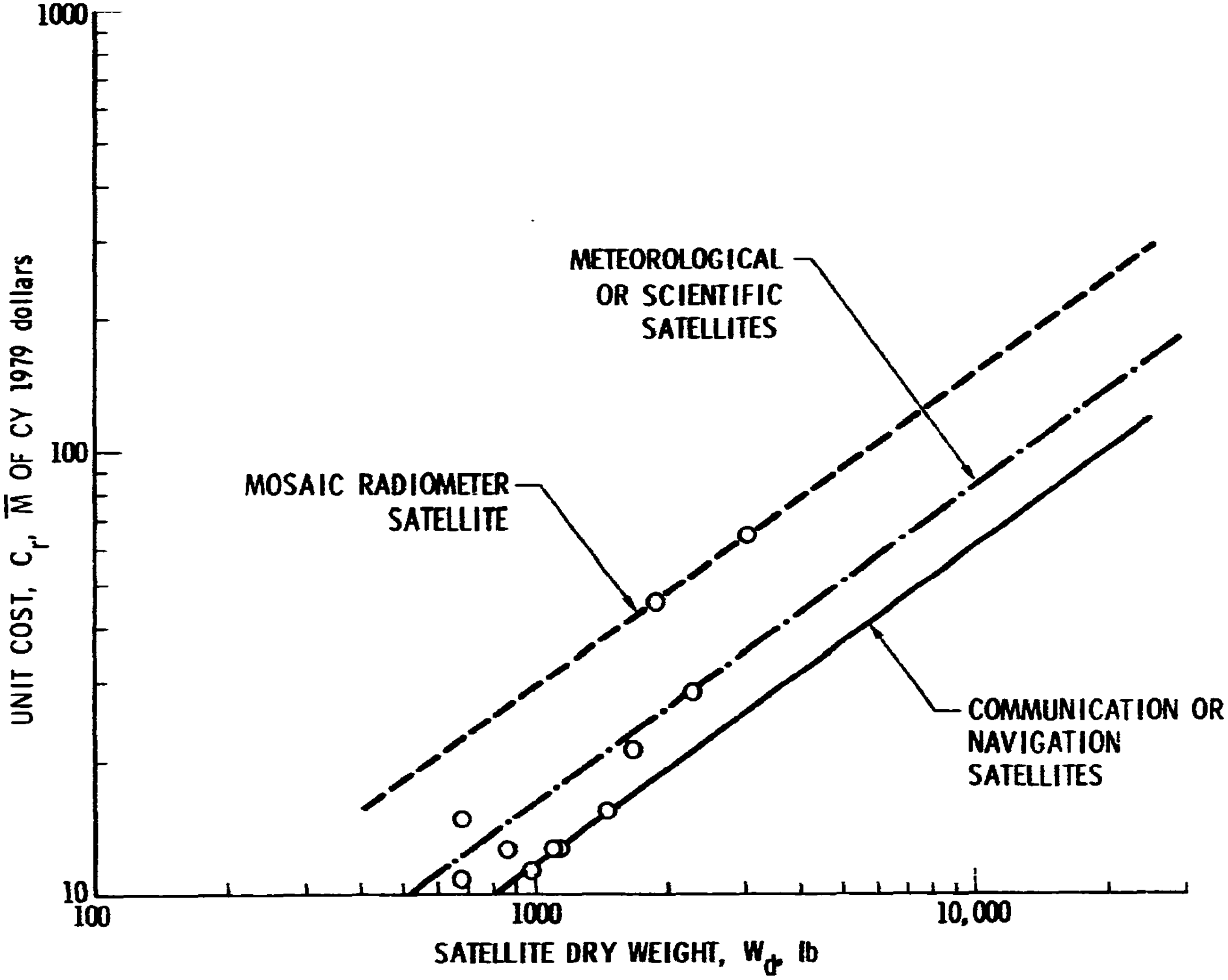

Figure 4. Recurring Satellite Costs

Only one data point represented a mosaic radiometer satellite in Figure 3, and it was decided to use that point for extrapolation to other such types. Accordingly, the equation for mosaic radiometer satellites is the same as Eq. (3), except that "a" equals 1.09.

The same procedure was applied to the data shown in Figure 4 to obtain unit cost CERs. Satellites were stratified by three categories: (1) mosaic radiometer, (2) meteorological and other scientific, and (3) communications and navigation. The basic equation is

$$C_r = aF_y W_d^{0.731} \qquad (4)$$

where

C_r = unit cost (recurring) in millions of constant CY 1979 dollars for 1979 technology

a = 0.187 for mosaic radiometer satellite

a = 0.102 for meteorological or other scientific satellite

a = 0.075 for communications or a navigation satellite

D. LEARNING CURVE APPLICATION

The unit cost Eq. (4) was derived from a cumulative average cost base normalized for 5 units. Provision must also be made for dealing with other production quantities. Certain unit cost models treat the two major cost components, production and sustaining engineering, separately.* It is hypothesized that production (excluding engineering) is best represented by a 90 percent log-linear cumulative average function — a 70 percent function applies to sustaining engineering. The composite of these two functions produces the cumulative average unit cost for any specified quantity. In applying CERs, from the present study, the mix between the two components of unit cost will not be known so that such a procedure cannot be used.

*For example, the Resource Analysis Directorate's "Spacecraft Cost Model."

A detailed examination of the costs of several satellites in the data base yielded a range of composite functions, the average of which is best represented by an 85 percent log-linear unit curve. It is recommended that such a function be used.

The equation for applying a log-linear unit curve is cumbersome to use; therefore, a convenient graphic representation has been developed and is presented in Figure 5. The log-linear unit function has been converted to a log-linear cumulative average form. From Figure 5, the factor F_n may be applied to the output of either Eq. (4) or the CER in Figure 4 to obtain the cumulative average unit cost for any desired quantity through 200. (The factor F_n will equal 1.0 when the desired quantity is five satellites because the data base is normalized to that quantity.) If the cost of follow-on quantities is needed, two readings from the curve are required — one for the first quantity and a second for the sum of the first plus the second quantity. Cumulative totals can then be calculated, and the difference will give total production cost for the second quantity of satellites.

In applying such learning curves to the CER output, the possibility of a nonflight prototype must be considered. If such a unit is required, it should be added to the flight quantity when developing cumulative average unit cost. Furthermore, to obtain proper categorization between nonrecurring and recurring cost, the average unit cost for the prototype should be added to nonrecurring cost, and only the flight units should be in total recurring cost.

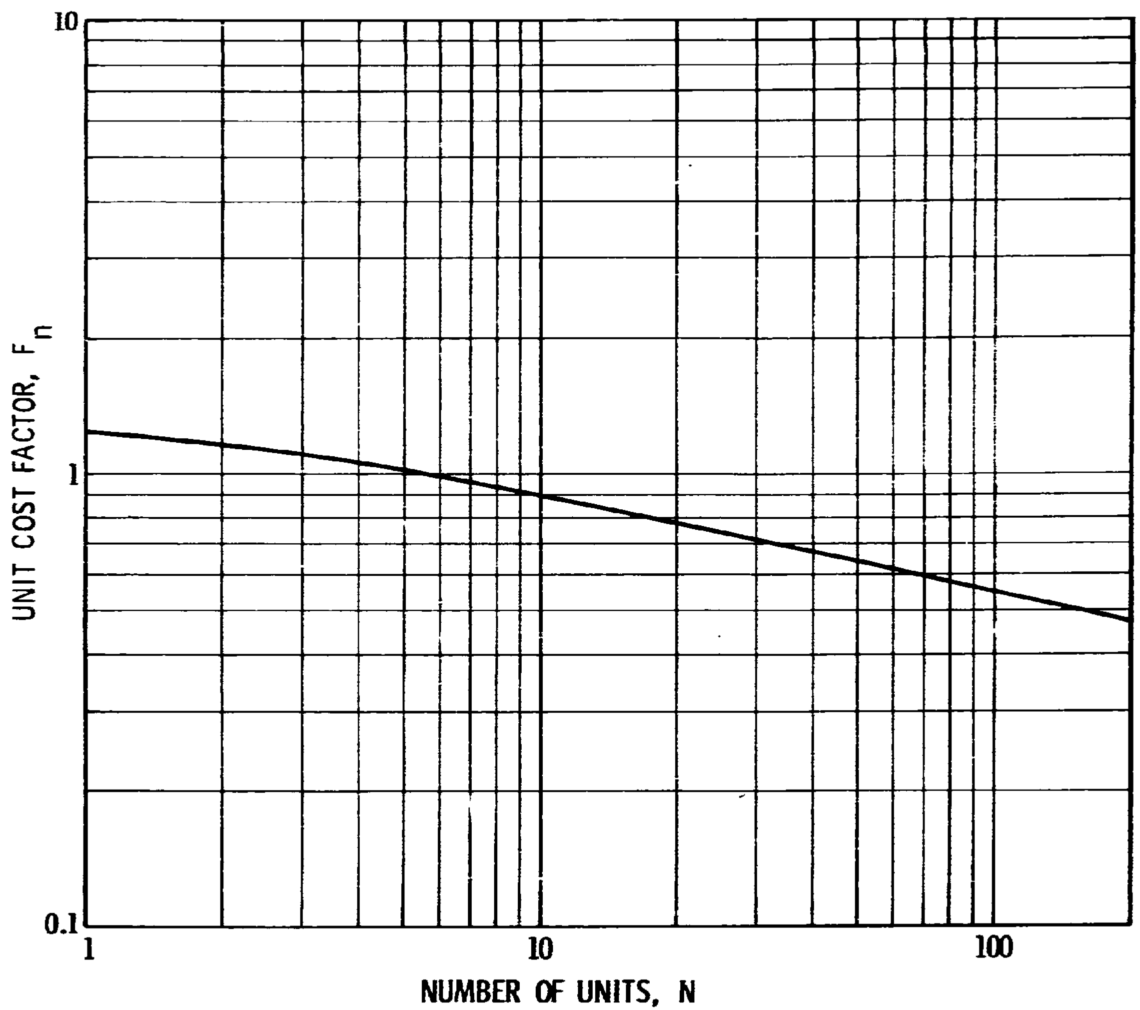

Figure 5. Cumulative Average Unit Cost Factors

III. ILLUSTRATIVE EXAMPLE

The following example is provided to demonstrate use of the CERs. Suppose that an estimate is needed of the cost to develop and produce a communications satellite system for the late 1980s. No detailed weight or performance information is available, and no split between communications and the other spacecraft subsystem weights is possible; however, it is known that eight satellites of approximately 3000 lb each are required for the system. The first of these satellites is to be launched in 1987. Technology commensurate with that time period is also hypothesized. Given a 1987 first launch date, from Eq. (2):

$$F_y = (0.96)^{87-79}$$

$$= 0.72$$

from Eq. (3):

$$C_d = 0.315(0.72)\ 3000^{0.678}$$

$$= 52 \text{ million (in constant CY 1979 dollars)}$$

and from Eq. (4):

$$C_r = 0.075(0.72)\ 3000^{0.731}$$

$$= 18.8 \text{ million (in constant CY 1979 dollars)}$$

The program requires one all-up prototype for qualification and other testing, however, it will not be flown. Accordingly, for cost-quantity purposes, nine units must be considered. From Figure 5, the F_n value is 0.9 at N = 9. When applied to the unit cost CER output, the adjusted average unit cost will be $16.9 million. Total RDT&E cost, total recurring cost, and total satellite program cost can be computed as follows:

$$\text{RDT\&E} = C_d + \$16.9\ \overline{M}\ (\text{prototype}) = 69 \text{ million (constant CY 1979 dollars)}$$

$$\text{Recurring} = 8 \text{ units} \times \$16.9\ \overline{M} = \underline{135}$$

$$\text{Total Satellite Program} \quad \underline{204} \text{ million (constant CY 1979 dollars)}$$